

# PZ Mon is a new synchronous binary with low mass ratio <sup>★</sup>

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## ABSTRACT

**Context.** Analysis of new radial velocity measurements of the active giant PZ Mon is presented.

**Aims.** Only in 2015 was reported that PZ Mon may be classified as RS CVn giant. At the same time was discovered the variability of radial velocity. However, lack of the data is not allowed to determine parameters of the system.

**Methods.** The measurements of radial velocity were performed using Radial Velocity Meter installed at the Simeiz 1-m telescope of the Crimean Astrophysical Observatory and using echelle spectrographs installed at the 2-m Zeiss telescope of the Terskol Observatory and the 6-m telescope BTA of the Special Astrophysical Observatory of the Russian Academy of Sciences.

**Results.** We estimated parameters of this binary system including the  $\gamma$ -velocity  $25.5 \pm 0.3 \text{ km s}^{-1}$ , the period on the circular orbit  $P = 34.15 \pm 0.02$  days, the mass of the secondary component  $M_2 = 0.14 M_{\odot}$ , and the mass ratio  $q = 0.09$

**Conclusions.** The mass ratio is a smallest value among known RS CVn type giants. Combined with photometric data we conclude that PZ Mon is a system with synchronous rotation, and there is a big cool spotted area on the stellar surface towards to the secondary component that provides the optical variability.

**Key words.** (Stars:) binaries: general – Stars: individual: PZ Mon – Stars: kinematics and dynamics – Stars: variables: general – (Stars:) starspots

## 1. Introduction

PZ Mon (HD 289114,  $V \approx 9$  mag) is active K2III star type of RS CVn located at a distance of about 250 pc (Pakhomov et al. 2015). Early the star was classified as a red dwarf with rapid irregular variability (Samus et al. 2009), SIMBAD calls this star as a flare star based on several articles (e.g. Pettersen & Hawley 1989; Gershberg et al. 1999). Nevertheless, the photometric period of about 34 days was detected by periodogram analysis (Bondar & Prokof'eva 2007) which was attributed to the rotational modulation of the spotty star. This assumption was confirmed by Pakhomov et al. (2015) through comprehensive analysis of PZ Mon; the measured rotational velocity  $10.5 \text{ km s}^{-1}$  corresponds to the found period 34.14 days and the inclination of the rotation axis  $\sin i = 0.92$ . Classification of PZ Mon as a RS CVn type star was carried out by analysis of its spectrum which shows evidences of the chromospheric activity:  $H\alpha$  emission,  $D_3$  helium absorption, emission in core of strong lines of sodium and magnesium. The luminosities in UV and X-ray also agree with the luminosities of other RS CVn stars. The duality of PZ Mon, main characteristic of RS CVn stars, was discovered by observations of variability of radial velocity with a possible period of about 17 days. However, absent of the measurements of radial velocity throughout all phases not allowed to make the final conclusion about true values of the period and the amplitude. In this work we close this gap by new radial velocity measurements (Section 2), also presented determination of parameters of

the PZ Mon system (Section 3), analysis these data together with photometric data (Section 4), and discussion in Section 5.

## 2. Observations

The main observations (set #1) we obtained 2014 Oct. 24–Nov. 9 using Radial Velocity Meter (RVM) (Tokovinin 1987) installed at the Simeiz 1-m telescope of the Crimean Astrophysical Observatory. Zero point velocity was determined by observations of several IAU velocity standards each night.

Seven spectra of PZ Mon were obtained within two observational sets using the MAESTRO echelle spectrograph (the resolving power  $R=40000$ ) installed in the coude focus at the 2-m Zeiss telescope of the Terskol Observatory of the Institute of Astronomy of the Russian Academy of Sciences. The first set (#2) contains one spectrum taken at 2014 Dec. 15, the second (#3) has six spectra taken at 2015 Jan. 18–26 on the Wright Instruments CCD (1242x1152) (see the journal of observations in Table 1). The exposure time was from 0.5 up to 2.75 hours (depending on the weather conditions) which was divided into several parts to reduce influence of cosmic rays. The signal-to-noise ratio for each spectrum are presented in the last column of Table 1. For three nights (Dec. 15 and Oct. 23 27) spectrum of the IAU radial velocity standard  $\beta$  Gem was taken after PZ Mon. In addition, for each set we took spectra of scattered sunlight. Data have been reduced using the MIDAS package *echelle*. 88 echelle orders were extracted in the region of  $3530 - 10060 \text{ \AA}$  with the wavelengths calibrated via ThAr hollow-cathode lamp. The spectra normalization was performed with the blaze function obtained from exposures of the star  $\eta$  Uma. Each spectrum of PZ Mon was reduced separately, and then for each night these spectra

<sup>★</sup> Based on observations collected at the BTA telescope (Special Astrophysical Observatory, Russia) and Zeiss-2000 telescope (Terskol observatory of Institute of Astronomy, Russia)

**Table 1.** Characteristics of the spectral observations of PZ Mon.

Set	Data	Time UTC	Number of exposures	Total exposure time, sec	Total S/N
2	2014-12-15	22:14-00:21	4	7200	45
3	2015-01-18	20:28-23:23	4	9900	65
	2015-01-19	20:59-23:42	5	9000	90
	2015-01-20	23:26-23:56	1	1800	40
	2015-01-23	20:19-22:08	3	5400	75
	2015-01-24	20:21-21:23	2	3600	80
	2015-01-26	19:23-20:24	2	3600	60
4	2015-02-10	16:47-18:20	3	5400	120

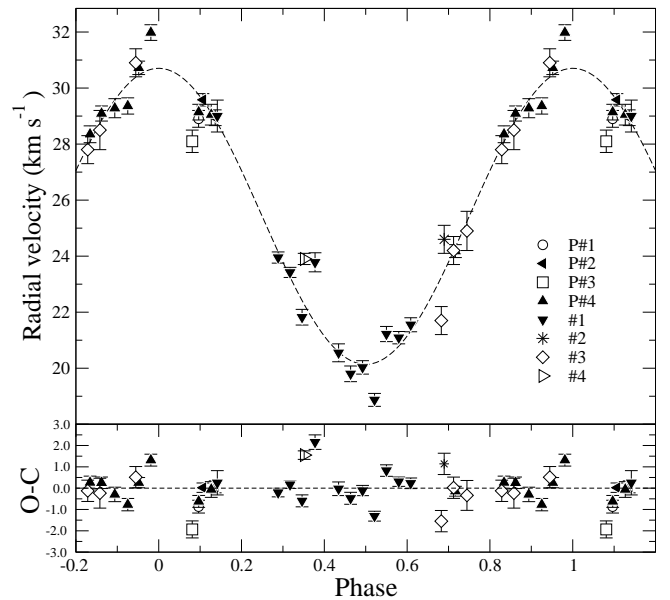
**Table 2.** Radial velocities of PZ Mon.

Set	JD 2450000+	$v_{\text{rad}}$ $\text{km s}^{-1}$	$\sigma v_{\text{rad}}$ $\text{km s}^{-1}$
1	6954.596	29.00	0.57
	6959.609	23.95	0.20
	6960.594	23.42	0.18
	6961.585	21.82	0.28
	6962.657	23.78	0.34
	6964.596	20.55	0.32
	6965.587	19.80	0.28
	6966.577	20.03	0.24
	6967.562	18.87	0.23
	6968.541	21.22	0.27
	6969.560	21.09	0.22
	6970.547	21.55	0.25
2	7007.458	24.6	0.5
3	7041.368	21.7	0.5
	7042.385	24.2	0.5
	7043.487	24.9	0.7
	7046.357	27.8	0.5
	7047.358	28.5	0.7
	7050.318	30.9	0.5
4	7064.210	23.91	0.16

were combined together with an allowance for the Earth's rotation.

One spectrum of PZ Mon (set #4) was obtained sequentially in three exposures at 2015 Feb. 10 using the NES echelle spectrograph with a slicer (the resolving power  $R=60\,000$ ) installed at the 6-m telescope BTA of the Special Astrophysical Observatory of the Russian Academy of Sciences on the e2v CCD42-90 (4632x2068). 54 echelle orders were extracted in the region of 3890 – 6980 Å with the wavelengths calibrated via ThAr hollow-cathode lamp. Similarly, each spectrum of PZ Mon was reduced separately, and then the three spectra were combined together with an allowance for the Earth's rotation.

Radial velocity (RV) was determined from PZ Mon spectrum in the region of 4800–6300 Å by cross correlation with the spectra of  $\beta$  Gem and scattered sunlight broadened to the rotational velocity of PZ Mon. The result are presented in Table 2 where the first column denotes the order number of observational sets (#1 is from RVM, #2, #3, and #4 are from spectral data), following are Julian day, the radial velocity  $v_{\text{rad}}$  and the errors. Also we reprocessed preview spectra of PZ Mon taken in 2012 (Pakhomov et al. 2015) and estimated RV by the same method  $v_{\text{rad}}=28.1\pm0.4\text{ km s}^{-1}$ .



**Fig. 1.** *Top:* Radial velocity measurements convolved with the period  $P=34.15$  d. Different sets are marked by different symbols. The labels correspond to the set number of Table 3 from (Pakhomov et al. 2015, started with "P") and Table 2 of current article. Dashed line is the theoretical radial velocity curve calculated by derived parameters. *Bottom:* Residual radial velocities (O-C).

**Table 3.** Parameters of PZ Mon system. Supposed values marked by a colon.

Parameter	PZ Mon A	PZ Mon B
$\gamma$	( $\text{km s}^{-1}$ )	$25.5\pm0.3$
$P$	( $\text{km s}^{-1}$ )	$34.15\pm0.02$
$K$	( $\text{km s}^{-1}$ )	$5.4\pm0.4$ : $0.5$ :
$\sigma_v$	( $\text{km s}^{-1}$ )	$0.9$
$v \sin i$	( $\text{km s}^{-1}$ )	$0.92\pm0.25$
$M$	( $M_\odot$ )	$1.5\pm0.5$ : $0.14\pm0.05$
$q = M_2/M_1$		$0.09\pm0.03$
$R$	( $R_\odot$ )	$7.7\pm1.9$ : $0.22$ :
$T$	(K)	$4700\pm100$ : $2700$ :
SpType	K2III	M7V:
$e$		$0.0\pm0.05$
$a$	(a.u.)	$0.018\pm0.005$ : $0.24\pm0.03$

### 3. Determination parameters of radial velocity curve

In (Pakhomov et al. 2015) we have described RV variation up to its maximum value. The set #3 shows very similar RV behavior that gives us the possibility to consider the sets in the common range of phases with the time difference  $444.3\pm0.5$  days. In this way, we probed values of the period as  $444.3/n$  where  $n$  is the integer number of orbital turns. For  $n = 13$  we obtained the best solution  $P = 34.18 \pm 0.04$  days. The period of about 17 days (Pakhomov et al. 2015) is not consistent with the observational set #1, probably, an error at the key point much more due to low resolution. To adjust the period value we use the fact that two pairs from the sets #2 and #4 from (Pakhomov et al. 2015) and one point from #1 of the current work has close RV and phase values. The estimated  $P=34.15\pm0.02$  days also agrees with the earliest RV measurement of Saar (1998). All available at this moment the RV values are combined in Fig. 1.

We applied Levenberg-Marquardt method to estimate the parameters of the RV curve:  $\gamma$  is the constant radial velocity of the

system PZ Mon ( $\gamma$ -velocity),  $K$  is the semiamplitude,  $e$  is the orbital eccentricity,  $\omega$  is the longitude of periastron. The following formula was used to fit the observations:

$$v_{rad} = \gamma + K [\cos(\theta + \omega) + e \cos \omega]$$

where  $\theta$  is the orbital true anomaly. The derived parameters are presented in Table 3 together with updated values of physical characteristics of PZ Mon binary system. Note, that the major semiaxis was estimated as  $a_1 = KP/(2\pi \sin i)$  for the primary component and  $a_2^3 = G(M_1 + M_2)P^2/(4\pi^2)$  for the secondary component, where we assumed  $i=i_{rot}=i_{orb}$ . The eccentricity  $e=0.0\pm0.05$ , we adopt  $e=0$ , so  $\omega$  was excluded. The fit curve drawn in Fig. 1 where in bottom O–C values are presented. The O–C values more than typical error of the measurements. The average deviation is about of  $0.9 \text{ km s}^{-1}$ , up to  $2.0 \text{ km s}^{-1}$  for two measurements.

The derived ephemeris of RV maximum is

$$JD = 2457052.2 \pm 0.3 + 34.15 \pm 0.02 E$$

#### 4. Photometric data

Since the photometric period of PZ Mon is stable and related to the stellar rotation (Pakhomov et al. 2015) and approximately equal to the RV period we decided to find a potential relationship between axial rotation of PZ Mon and orbital rotation of the secondary component.

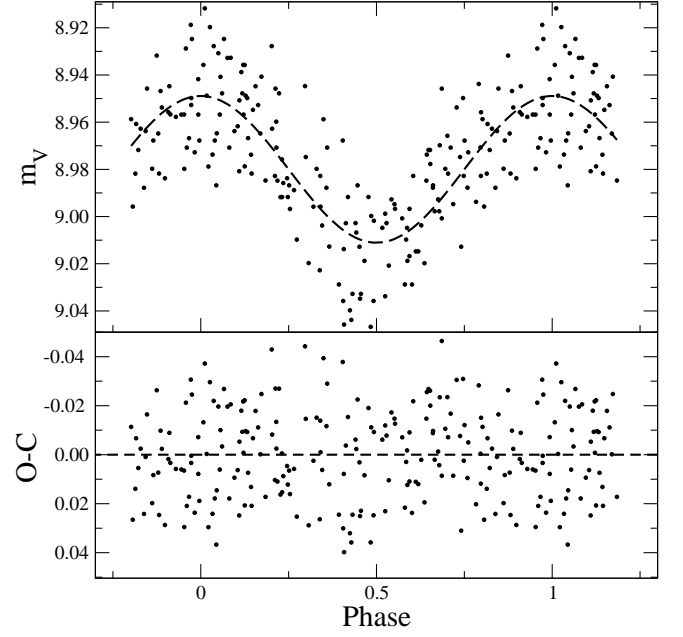
To derive the photometric ephemeris we used observations in V and I bands of the ASAS project (Pojmanski 1997, <http://www.astrouw.edu.pl/asas/>). The period of 2005–2009 (5 sets of observations) is more preferable due to expressed changes of the magnitude. The light curve convolved with  $P=34.13$  days is presented in Fig. 2 for V Johnson band and in Fig. 3 for I band. The typical error of magnitudes given by the ASAS is about of  $0.03\text{--}0.05^m$  but really the accuracy may be better that can be seen from the O–C values. In both case, to avoid the global trend we reduced the magnitudes to one of the observational sets. The changes in Fig. 2, 3 like the law of cosines with semiamplitude of about  $0.03^m$ . The ephemeris of maximum of brightness is

$$JD = 2454807.2 \pm 0.7 + 34.13 \pm 0.02 E$$

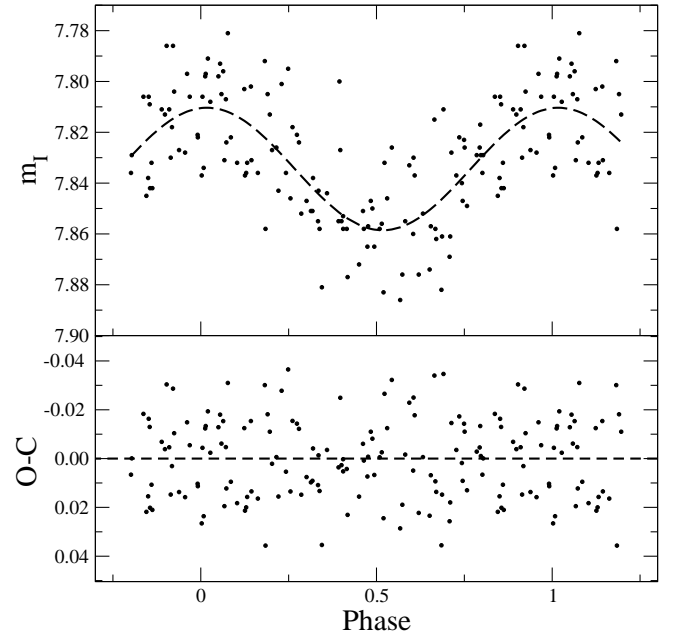
In Fig. 4 we present relative locations of the light and the radial velocity curves calculated from derived ephemerides. Because real changes of magnitudes are more complex due to irregular nature the light curve in Fig. 4 synthesized with the constant average magnitude of  $9^m$  and the constant semiamplitude of  $0.03^m$ . Fig. 4 shows the phase shift between the curves  $\Delta\phi=0.78\pm0.04$  for  $P=34.13$  days and  $0.74\pm0.04$  for  $P=34.15$  days. Thus, the shift provides the lead of the photometric curve by one fourth of the period. However, this fact refers to the average picture. Probably, the deviations in Fig. 2 and Fig. 3 may partially related to the differential rotation of PZ Mon and the change positions of the active regions which are responsible for the observable variability.

##### 4.1. Model of PZ Mon system

Minimum of the brightness in Fig. 4 matches to the  $\gamma$ -velocity. Such picture may observed if a cool spot on the stellar surface lie on a line connecting the stars. Probably, this spot is a effect of the activity due influence of the secondary component and is a main reason of photometric variability (see top of Fig. 4).



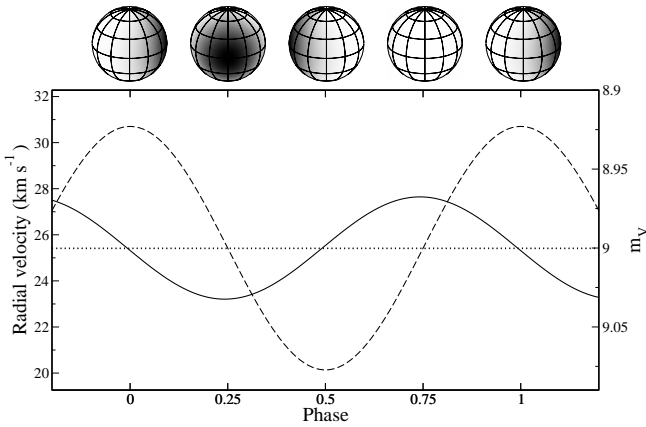
**Fig. 2.** *Top:* Light curve in V band from the ASAS data (2005–2009) convolved with  $P=34.13$  days and fitted by cosines law (*dashed line*). *Bottom:* Difference between observations and calculations ( $\sigma = 0.02^m$ ).



**Fig. 3.** *Top:* Light curve in I band from the ASAS data (2005–2009) convolved with  $P=34.13$  days and fitted by cosines law (*dashed line*). *Bottom:* Difference between observations and calculations ( $\sigma = 0.02^m$ ).

Typically, light curve of RS CVn stars shows a flat plateau but, in case of PZ Mon, it like the law of cosines with semiamplitude of about  $0.03^m$  that may be caused by big spotted area with size of about semisphere and with the average photosphere temperature of  $40\text{--}50 \text{ K}$  below relative to opposite stellar surface.

We modelled two simple cases for equatorial spotted area. In the first case, the spotted area of radius  $90$  degree has constant intensity  $I_{spot}$  relative unspotted area. In the second case, the spotted area has intensity distributed by gaussian  $I = I_{spot}e^{-(r/90)^2}$ , where  $r$  is the angular distance from the spot center. The result



**Fig. 4.** Radial velocities (dashed line) and photometric (thin line) ephemerides. The last is in assuming a constant of the average magnitude ( $9^m$ ) and the semiamplitude ( $0.03^m$ ). Top: the apparent position of the main spotted area.

of calculations is  $I_{spot}=0.943, 0.915$  for these cases, respectively, that provides observed behavior and the amplitude of the light curve. Also we calculated influence of the spots on the RV measurements using given distribution of the intensity. The maximal changes  $\Delta v_{rad}=0.14$  and  $0.10 \text{ km s}^{-1}$  were obtained which lower than the errors in our measurements.

If the spotted area represented by evenly distributed spots on the apparent semisphere then we can calculate the increase of the filling factor on the more spotted area relative to the opposite side. Alekseev & Bondar' (2006) have estimated the filling factor  $S_1 \approx 20\%$  for the semisphere which provides maximum of the brightness. The ratios of maximal and minimal intensities is  $\frac{I_2}{I_1} = \frac{1-S_2(1-\beta)}{1-S_1(1-\beta)}$ , where  $\beta \ll 1$  is the ratio of intensity in the spots and real unspotted stellar surface. Using our value  $I_{spot} = \frac{I_2}{I_1} = 0.943$  we calculated  $S_2=24\%$  which slightly depends on  $\beta$ . Thus, the difference of the filling factor between semispheres with minimal and maximal spots number is about 4%.

## 5. Discussion

The parameters of the RV curve point to the secondary star of mass  $0.14 M_{\odot}$  at the circular synchronous orbit with the major semiaxis  $a=0.23 \text{ a.u.} = 35 \text{ millions km} = 6.5 R_{PZ}$ . The star may be a red dwarf with the effective temperature  $T_{eff} \approx 2700 \text{ K}$ , and the radius  $R \approx 0.22 R_{\odot}$ . In the sky this is a star of magnitude  $19^m$  located at an angular distance of  $0.001''$  from PZ Mon that making it invisible object from the Earth. We exclude a possibility that the variability is caused by an eclipse. In system of PZ Mon can occur eclipse if angle of the inclination more than  $81^\circ$  ( $\sin i > 0.988$ ). In this case, the apparent variation of magnitudes will be too small, about  $0.0008^m$ . To provide observed amplitude  $\sim 1/18$  of the stellar disk should be closed, then radius of the secondary star should be  $0.23 R_{PZ}$  or  $1.8 R_{\odot}$  that is not consistent with the mass of the object.

We observe difference between phases  $\Delta\phi = 0.75$  of RV and light curves. The same effect was observed for other some RS CVn stars. Bubar et al. (2011) do not notice the effect in V474 Car but available data allow us to calculate it, we found  $\Delta\phi = 0.75$ . Muneer et al. (2010) analyzed photometric data along orbital modulation and found maximum of the brightness around 0.25p and 0.75p depending on the spot activity. Zhang & Zhang (2007) studied RS CVn type star DV Psc, the difference 0.75p between photometric and radial velocity phases

is shown in Fig. 3 of its article. Also we can see narrow flux minimum corresponds to the RV average value. Authors concluded that these effects can be caused by the cool spot towards to the secondary component. Oláh et al. (2002) perform the doppler mapping of short period synchronous RS CVn-type giant UZ Lib. All maps linked to the orbital ephemeris show minimum of brightness at the phases about of 90 and 270 degrees, i.e. main spots located towards to the secondary component and on the opposite site. However, in most cases, doppler mapping of RS CVn stars does not show stable locations of big spots. To clarify the nature of PZ Mon activity we need the spectral monitoring and the doppler mapping of its surface.

This effect of activity is expected. Indeed, the secondary component should affect to main star which demonstrates chromospheric activity. Owen et al. (1976) have detected radio emission from RS CVn binary star HR 1099. Bunton et al. (1986) observed the variations of radio from spots related to the stellar rotation and explained the source of radio by gyro-synchrotron radiation. Lestrade et al. (1984) using VLBI estimated the size of radio source as comparable diameter of active star. Trigilio et al. (2001) observed AR Lac variable of RS CVn type also using VLBI. The obtained data indicate a source size close to the separation of the binary components, suggesting the possibility of an emitting region located between the system components. Note, many RS CVn type stars were contained in the FIRST catalog of radio sources (White et al. 1997). However, not all RS CVn giants are sources of radio emission. PZ Mon is one of them, it was not marked as a radio source. Richards & Russell (1998) searched the tidal effects by radio emission at difference rotational phases for two RS CVn type stars but not found.

PZ Mon has small mass ratio of the components  $q = M_2/M_1 = 0.09$  which is the smallest value among known RS CVn giants. At the same time, the system is synchronous. We analyzed available data to find analogues of PZ Mon by mass ratio among long-periodical ( $P > 20 \text{ d}$ ) RS CVn giants. In the General Catalog of Variable Stars (Samus et al. 2009) there are 20 confirmed giants of RS CVn type, half of them are long-periodical. While among all RS CVn stars this portion is about of 8%. In the Catalog of chromospherically active binary stars (Eker et al. 2008) there are 164 RS CVn type stars, 64 among them has period more than 20 days. While amount of giants is 78 and 52, respectively. Thus, in the family of long-periodical RS CVn stars giants dominate. We found four analogues with minimal mass of the secondary component: V1379 Aql (data of Jeffery et al. 1992), AZ Psc (data of Pourbaix et al. 2004; Fekel & Henry 2005) and V4138 Sgr (data of Fekel & Henry 2005). The comparison of its parameters together with PZ Mon presented in Table 4. All comparable systems are asynchronous and they shown more noticeable changes of magnitudes exclude last one FG Cam. They have the same spectral class and close values of luminosities ratio of X-rays and bolometric  $L_X/L_{bol}$ . Unlike PZ Mon they are sources of radio and infrared emission. Three asynchronous stars may have hot components. V1379 Aql has apparent in UV hot subdwarf of temperature of about 25 000–30 000 K. In UV region V1379 Aql shows only one chromospheric line Mg II; AZ Psc has noisy spectrum without visible lines; V4138 Sgr, contrariwise, has strong spectral lines (Wamsteker et al. 2000) with the luminosities comparable and exceeding of PZ Mon. UV luminosities calculated from fluxes in terms of GALEX (Bianchi et al. 2011): FUV  $\lambda_0=1539 \text{ \AA}$ ,  $\Delta\lambda=1344\text{--}1786 \text{ \AA}$ , NUV  $\lambda_0=2316 \text{ \AA}$ ,  $\Delta\lambda=1771\text{--}2831 \text{ \AA}$ . Perhaps, big amplitude of analogues related to high temperature of the secondary component. If this assumption is true

**Table 4.** Comparison of the parameters of RS CVn type analogues of PZ Mon by the spectral type, the period, and the mass.

Parameter		PZ Mon	V1379 Aql	AZ Psc	V4138 Sgr	FG Cam
$P_{orb}$	(days)	34.15	20.66	47.12	13.05	33.83
$P_{rot}$	(days)	34.13	25.64	91.2	59	31.95
$V_{sini}$	(km s <sup>-1</sup> )	10.5	~19	~4	~5	12.4
$K$	(km s <sup>-1</sup> )	5.4	13.1	10.35	9.89	5.28
$M_1$	( $M_{\odot}$ )	1.5	2.4	1.5	1.5	3.3
$M_2$	( $M_{\odot}$ )	0.14	0.31	0.24	0.24	0.38
$q = M_2/M_1$		0.09	0.13	0.16	0.16	0.12
SpType <sub>1</sub>		K2III	K0III	K0III	K1III	K2III
SpType <sub>2</sub>		M7V?	sdB	dF	dB	M0III
$\Delta m_V$	(mag)	0.03	0.30	0.33	0.3	0.07
distance	(pc)	250	270	170	80	257
source of		UV,X	IR,UV,X	IR,UV,X	Rad,IR,UV,X	Rad,IR,X
$\log(L_{bol}/L_{\odot})$		1.4	1.7	1.6	1.1	2.1
$\log(L_X/L_{bol})$		-4.5	-4.8	-4.3	-4.5	-4.6
$\log(L_{FUV}/L_{bol})$		-4.2	-1.9	-3.4	-4.4	-4.7
$\log(L_{NUV}/L_{bol})$		-3.1	-2.0	–	-2.8	-3.3
IR excess at	( $\mu$ m)	–	60,100	100	100	60,100

then little amplitude of PZ Mon and FG Cam would indicate the low temperature of the secondary component. All comparable stars show excess in infrared starting from 60–100  $\mu$ m that may points to circumstellar shell.

## 6. Conclusions

We performed the radial velocity measurements of the active giant PZ Mon and determined the parameters of this binary system. The mass ratio of the components  $q = 0.09$  is a smallest value among known RS CVn giants. Within errors of the derived periods we conclude that the system is synchronous. However, we need to improve the conclusion by new photometric and radial velocity measurements.

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